PALeo constraints on SEA level rise (PALSEA): ice-sheet and sea-level responses to past climate warming

Anders E. Carlson [a,*], Andrea Dutton [b], Antony J. Long [c], Glenn A. Milne [d]

[a] *College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, Corvallis, OR, USA 97331*

[b] *Department of Geological Sciences, University of Florida, Gainesville, FL, USA 32611*

[c] *Department of Geography, Durham University, Durham DH1 3LE, UK*

[d] *Department of Earth and Environmental Sciences, University of Ottawa, ON, K1N 6N5, Canada*

*acarlson@coas.oregonstate.edu

ABSTRACT

Here we summarize the motivation and issues surrounding the responses of ice sheets and sea level to past climate warming as part of the PALeo constraints on SEA level rise (PALSEA) working group. Papers in this special issue of *Quaternary Science Reviews* focus on the timescale of glaciations during the late Pliocene, the magnitude of ice-sheet fluctuations and volume leading up to and during the last glacial maximum, the timing and persistence of ice-sheet impacts on deglacial and future relative sea-level change, and relative sea-level change during peak interglacial climate. A more dynamic cryosphere is noted under both late Pliocene and last glacial cycle climate conditions, while relative sea-level changes during the last deglaciation appear to correspond closely with individual ice-sheet deglaciation. Lastly, relative sea-level change during peak interglacial conditions may have fluctuated by as much as a meter, although the sources of such variability (Greenland, Antarctica or elsewhere) remain elusive.

1. Introduction

The greatest uncertainty in projecting future sea-level rise lies in the responses of Earth's remaining ice sheets (e.g., Alley et al., 2005; Church et al., 2013; Clark et al., 2016). The observational period of sea level and ice-sheet mass balance spans at best only the last century, at least partly exacerbating present uncertainty in future sea-level rise (Church et al., 2013). In contrast, the geologic record provides valuable archives of how ice sheets and sea level have responded to past climate variability, particularly during periods of climate warming (e.g., Alley et al., 2005; Dutton et al., 2015a; Clark et al., 2016). The information contained in the geological record can therefore help assess the relationship between ice sheets, sea level and climate change over multi-millennial to century timescales.

PALeo constraints on SEA level rise 2 (PALSEA2) is a Past Global Changes (PAGES) working group and international focus group of the Coastal and Marine Processes commission in International Union for Quaternary Research (INQUA). PALSEA brings together observational scientists and ice-sheet, climate and sea-level modelers in order to better define and interpret observational constraints on past sea-level rise and improve our understanding of ice-sheet responses to climate change. This PALSEA *Quaternary Science Reviews* special issue addresses these topics by examining orbital-scale sea-level changes during the late Pliocene (Grant et al., 2018), ice-sheet extent and volume prior to and during the last glacial maximum (Carlson et al., 2018; Pico et al., 2018; Simms et al., 2019), relative sea-level changes following the last glacial maximum (Barnett et al., 2019; Romundset et al., 2018; Simms et al., 2018; Xiong et al., 2018; Yokoyama et al., 2019; Yousefi et al., 2018), and full interglacial relative sea-level change during the last interglaciation (Skrivanek et al., 2018) (Fig. 1, 2b). Here we summarize and contextualize the findings of these studies and lay a road map for future research on past ice-sheet and sea-level change.

2. Sea level variability in warm times

The late Pliocene of 3,300 to 3,000 ka (Fig. 2b) is the last time that atmospheric CO_2 concentrations were around present-day values (Fig. 2c), providing an important long-term constraint on the response of the cryosphere to this radiative forcing (Alley et al., 2005; Dutton et al., 2015a). However, geophysical processes such as mantle dynamic topography have likely caused sea-level indicators to change in elevation since the time of their formation. This complicates the procedure to estimate global-mean sea level from these records (e.g., Dutton et al., 2015a). However, orbital-scale fluctuations in temperature and ice volume certainly occurred across this 300-ka time window followed by the descent of the Earth into the Pleistocene ice ages (Fig. 2a, b).

Grant et al. (2018) provide a new insight into late-Pliocene changes in relative sea level in the Whanganui Basin, New Zealand (1 on Fig. 1). Here, a marginal marine basin records 23 sedimentary cycles related to the rise and fall of local sea level from 3,300 to 2,600 ka, which are dated by magnetostratigraphy, biostratigraphy and tephra chronology that are largely independent of orbital tuning. Interestingly, sea level fluctuated at a 20-ka timescale 3,300 to 3,000 ka, then switched to a 40-ka timescale 3,000 to 2,600 ka; these periodicities are reminiscent of, respectively, precession and obliquity timescales of Quaternary ice-sheet fluctuations. Grant et al. (2018) note that they can find a one-to-one correlation between their sea-level changes and a high-resolution benthic δ^{18}O record from the eastern tropical Pacific (Mix et al., 1995), which is not found in the benthic δ^{18}O stack in Fig. 2b (Lisiecki & Raymo, 2005). Spectral power at the precession frequency is largely lacking in the benthic δ^{18}O stack across the late Pliocene to early Quaternary when that due to obliquity is dominant (Raymo et al., 2006; Meyers & Hinnov, 2010). Grant et al. (2018) suggest that this mismatch could be due to smoothing of the benthic δ^{18}O records in the stacking process or the low resolution of some of the contributing records.

3. The last glacial cycle

Individual ice-sheet sources of sea-level change prior to the last glacial maximum are difficult to interpret because the terrestrial record of ice-sheet extent (and inferred volume) is largely removed by the ice sheets during the last glacial maximum (e.g., Clark et al., 1993; Dyke et al., 2002) and far-field sea level indicators may not have a unique solution for individual ice-sheet sources (e.g., Peltier & Fairbanks, 2006; Lambeck et al., 2014). However, Pico et al. (2017) were able to use relative sea-level indicators along the eastern seaboard of the United States to document a smaller Laurentide ice-sheet volume during marine isotope stage (MIS) 3, 60-26 ka (2,3 on Fig. 2b), than is used in current sea level-ice volume solutions (e.g., Peltier & Fairbanks, 2006; Lambeck et al., 2014). Relatively unique geological constraints are preserved in the Hudson Bay lowlands that indicate ice-free conditions in the center of the Laurentide ice sheet for the first half of MIS 3 (Fig. 1) (Dalton et al., 2016; 2019). Pico et al. (2018) present a revised ice model from the 2017 study (3 on Fig. 1), which better agrees with the geological constraints. Carlson et al. (2018) also addressed MIS 3 Laurentide ice-extent changes, documenting a late MIS 3 advance to near the last glacial maximum extent of the Laurentide ice sheet by ~39 ka (2 on Fig. 1). The timing of this MIS 3 maximum is in agreement with other Laurentide ice-margin constraints (Wood et al., 2011; Ceperley et al., 2019 in press) and requires rapid growth of the Laurentide ice sheet. In this vein, Carlson et al. (2018) and Pico et al. (2018) use independent dynamic ice-sheet simulations to show that rapid advance is glaciologically possible, and was the case leading into the last glacial maximum.

While not a warming climate, the last glacial maximum does set the stage for the last period of global warming (the last deglaciation) prior to that of the last century. However, the sources of the sea-level lowering during the last glacial maximum has been debated since the first chronological constraints showed that most Quaternary ice sheets were concurrently at their last glacial maximum extent (Donn et al., 1962; Denton & Hughes, 1981; Clark & Mix, 2002; Clark et al., 2009; Clark & Tarasov, 2014). Specifically, individual ice-sheet volumes do not sum up to the estimated eustatic sea-level lowering at the last glacial maximum (4 on Fig. 2b). Simms et al. (2019) revisit this plaguing issue by looking for additional sources of sea-level lowering beyond global ice sheets (4 on Fig. 1). They estimate a low-stand contribution from ocean steric contraction of ~2.4 m and groundwater storage of ~1.4 m. While these contributions help to push the budget towards balance, there still remains a considerable deficit, implying error in either the ice-sheet reconstructions or the volume estimated from far-field sea-level records.

For the last deglaciation, four studies focus on relative sea-level changes from near, intermediate, and far-field locations (numbers 5-8 on Fig. 1). Yousefi et al. (2018) assess the glacial isostatic adjustment (GIA) in sea-level indicators along the western Northern American coast from southern Canada to the southern United States. They found significant mantle viscosity variability across this tectonically active region. They demonstrate that GIA can contribute up to ~20 cm in sea-level rise along this coast by 2100 C.E. and so should be included in future projections for this region. Their results also indicate that all of the glaciological reconstructions considered (~25 in total) include the onset of major deglaciation that is too early to be consistent with the deglacial relative sea-level indicators. This is important as new ^{10}Be surface exposure ages for this region indicate initial coast deglaciation at ~17 ka, even earlier than in the ice-sheet loading histories (Darvill et al., 2018; Lesnek et al., 2018). Rectifying these apparently disparate observations would require relatively minimal and localized ice-margin retreat at ~17 ka, followed several millennia later by more significant retreat and deglaciation, with implications for the timing of when an ice-free coast could form along western North America for human migration southwards into the contiguous United States.

Romundset et al. (2018) present a new near-field relative sea-level record for southeastern Norway (6 on Fig. 1) at century-scale resolution. A major inflection in relative sea-level fall at ~9.5 ka shows excellent agreement with the timing of full Scandinavian ice sheet deglaciation dated by ^{10}Be surface exposure ages (Cuzzone et al., 2016). Later variations in the rate of sea-level fall (e.g., event around 7 ka) likely reflect sea-surface height signals from distant ice sheets. The relative sea-level data resulting from this study will provide important constraints on GIA models and therefore for improving predictions of future sea-level change in this region.

Xiong et al. (2018) and Yokoyama et al. (2019) (7 and 8, respectively, on Fig. 1) update far-field relative sea-level records from the South China Sea and northern Indian Ocean, respectively. Xiong et al. (2018) note an acceleration in relative sea-level rise at ~9.5 ka with a slowing sea-level rise at ~7.0 ka. These are times of known acceleration in Laurentide ice sheet retreat and final deglaciation (Carlson et al., 2008a; Ullman et al., 2016). Yokoyama et al. (2019) document the timing of cessation in global mean sea-level rise to be ~4 ka, placing an important constraint on global ice volume change following this time. These findings agree with prior far-field assessments (Hallmann et al., 2018) and inferences from individual ice-sheet records (Cuzzone et al., 2016; Ullman et al., 206). These findings would also place the end of the last deglaciation at ~4 ka, meaning true peak interglacial conditions, as defined by a maximum in global mean sea level, only occurred during approximately the last 1/3 of the Holocene.

4. Interglacial relative sea-level change

The last interglaciation (128-116 ka) is three times as long as the Holocene interglaciation (4.0-0 ka) (Dutton et al., 2015b; Barlow et al., 2018; Polyak et al., 2018; Yokoyama et al., 2019), if defined by global mean sea level at or above pre-industrial levels (Fig. 2b). Although global mean sea-level change of the last 4 ka has been on the centimeter to decimeter scale (e.g., Kopp et al., 2016), last interglacial sea level may have fluctuated on a meter scale (e.g., Kopp et al., 2013). Given the implications for ice-volume changes, a major question then is determining the time period over which such a fluctuation occurred. Helping in solving this question, Skrivanek et al. (2018) revisit coral elevations and stratigraphy on the Bahamas (9 on Fig. 1) where such a sea-level oscillation was previously suggested (Thompson et al., 2011). Skrivanek et al. (2018) confirm a transient relative sea-level fall and rise of at least 1 m in ~1 ka. This finding does not necessarily conflict with a new sea-level record from the Mediterranean that could rule out a larger sea-level oscillation of >1 m in magnitude at that location (Polyak et al., 2018). The cause of this oscillation at the Bahamas is, however, unknown (Barlow et al., 2018).

Simms et al. (2018) and Barnett et al. (2018) provide two new relative sea-level records to document peak interglacial Holocene change at near-field sites on the Antarctic Peninsula (10 on Fig. 1) and eastern Quebec (11 on Fig. 1), respectively. Simms et al. (2018) find changes in sea level along the Antarctic Peninsula are likely recording recent ice-sheet loading history rather than GIA following the last deglaciation. In particular, a late-Holocene increase in the rate of sea-level fall could reflect recent ice retreat following a readvance after the last deglaciation, similar to observations to the south of the West Antarctic ice sheet (Bradley et al., 2015; Kingslake et al., 2018). This means that relative sea-level data along the Antarctic Peninsula may not be helpful in constraining last glacial maximum ice volume (Simms et al., 2019), due to the non-monotonic loading history and the low mantle viscosity of the region resulting in a greater sensitivity to relatively recent (past few ka) loading changes. Barnett et al. (2018) document both secular and residual trends in sea-level rise in eastern Quebec. They note a potential glacier mass loss signal following the Little Ice Age along with influences from the North Atlantic Oscillation, Northern Hemisphere temperatures and Atlantic meridional overturning circulation. Their results highlight the complexity in isolating different drivers and thus estimating global mean sea-level change from local relative sea-level change (e.g., Kopp et al., 2016). Both Simms et al. (2018) and Barnett et al. (2018) show the difficulty in defining a baseline period in sea level against which current changes can be assessed and future predictions made.

5. Outlook

The papers in this *Quaternary Science Reviews* special issue suggest important avenues for future research. For the late Pliocene, documenting the magnitude of relative sea-level change in New Zealand, once corrected for GIA and other tectonic land motions, would provide critical information on the glacial-interglacial scale of ice-volume change under greenhouse gas concentrations similar to present. Comparing this independently dated record of sea level to individual ice-sheet records (e.g., Jansen et al., 2000; Patterson et al., 2014; Blake-Mizen et al.,

2019) could test the hypothesis of Raymo et al. (2006) on the lack of precession in the benthic $\delta^{18}O$ stack (Fig. 2b) during the late Pliocene to early Pleistocene, which could also help in understanding the dynamics that led to bipolar Quaternary glaciations.

For the last glacial cycle, sea-level budgets are still incomplete. The extent of ice sheets during MIS 3 (as well as MIS 4 and 5a-d) requires further investigation as does the underlying causes of the differing ice-sheet extents (e.g., Larsen et al., 2018). Solving the last glacial maximum sea-level budget should be a critical point of study as over 55 years of research on this topic has not resulted in closure. This budget problem persists into the deglaciation and the Holocene. At present, the early Holocene sea-level budget calls for more ice in Antarctica than most reconstructions have at the last glacial maximum (Cuzzone et al., 2016). Likewise, the sources of sea-level rise after ~7 ka when the Laurentide ice sheet is deglaciated (Ullman et al., 2016) have to be rectified against the recent observations presented in this special issue. The Greenland ice sheet was smaller than present and regrew by a modest volume over the late Holocene (e.g., Larsen et al., 2015). Similarly, there is growing evidence that the West Antarctic ice sheet was also smaller than present during the Holocene, regrowing in the late Holocene (Bradley et al., 2015; Kingslake et al., 2018) as did most glaciers and ice caps in the Northern Hemisphere (e.g., Solomina et al., 2015). How these cryospheric changes translate into reconstructions of late-Holocene global mean sea level changes (e.g., Kopp et al., 2016) should be investigated.

Lastly, whether one or more global mean sea-level oscillations occurred during the last interglaciation should be resolved. Here, the timing and magnitude of individual ice-sheet retreat histories may also provide important insight. For instance, the Greenland ice sheet retreated across the last interglaciation, reaching a minimum near the end of the interglacial period (Carlson et al., 2008b). While no direct evidence exists at present, the Antarctic ice sheets may have been smaller than present early in the last interglaciation (Dutton et al., 2015b), which can be simulated by ice-sheet models (e.g., DeConto & Pollard, 2016; Edwards et al., 2019). A global mean sea-level fall and rise could reflect the competing histories of these two ice sheets, with Antarctica losing mass then regrowing while Greenland continued to retreat through the interglaciation, rather than retreat and readvance of one ice sheet (Carlson, 2013).

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References

Alley, R.B., Clark, P.U., Huybrechts, P., Joughin, I., 2005. Ice-sheet and sea-level changes. Science 310, 456-460.

Barlow, N.L.M., McClymont, E.L., Whitehouse, P.L., Stokes, C.R., Jamieson, S.S.R., Woodroffe, S.A., Bentley, M.J., Callard, S.L., Ó Cofaigh, C., Evans, D.J.A., Horrocks, J.R., Lloyd, J.M., Long, A.J., Margold, M., Roberts, D.H., Sanchez-Montes, M.L., 2018. Lack of evidence for a substantial sea-level fluctuation within the Last Interglacial. Nat. Geosci., doi: 10.1038/s41561-018-0195-4.

Barnett, R.L., Bernatchez, P., Garneau, M., Brain, M.J., Charman, D.J., Stephenson, D.B., Haley, S., Sanderson, N., 2019. Late Holocene sea-level changes in eastern Québec and potential drivers. Quat. Sci. Rev. 203, 151-169.

Bartoli, G., Hönisch, B., Zeebe, R.E., 2011. Atmospheric CO_2 decline during the Pliocene intensification of Northern Hemisphere glaciations. Paleoceanography 26, doi: 10.1029/2010PA002055.

Bereiter, B., Eggleston, S., Schmitt, J., Nehrbass-Ahles, C., Stocker, T.F., Fischer, H., Kipfstuhl, S., Chappellaz, J., 2015. Revision of the EPICA Dome C CO_2 record from 800 to 600 kyr before present. Geophys. Res. Lett. 42, doi: 10.1002/2014GL061957.

Blake-Mizen, K., Hatfield, R.G., Stoner, J.S., Carlson, A.E., Xuan, C., Walczak, M., Lawrence, K.T., Channell, J.E.T., Bailey, I., 2019. Southern Greenland glaciation and Western Boundary

Undercurrent evolution recorded on Eirik Drift during the late Pliocene intensification of Northern Hemisphere glaciation. Quat. Sci. Rev. 209, 40-51.

Bradley, S.L., Hindmarsh, R.C.A., Whitehouse, P.L., Bentley, M.J., King, M.A., 2015. Low post-glacial rebound rates in the Weddell Sea due to Late Holocene ice-sheet readvance. Earth Planet. Sci. Lett. 413, 79-89.

Carlson, A.E., 2013. Does sea-level volatility indicate individual ice-sheet volatility during the last interglaciation? PALSEA2 Meeting Abstract, Rome, Italy.

Carlson, A.E., LeGrande A.N., Oppo, D.W., Came, R.E., Schmidt, G.A., Anslow, F.S., Licciardi, J.M., Obbink, E.A., 2008a. Rapid early Holocene deglaciation of the Laurentide Ice Sheet. Nat. Geosci. 1, 620-624.

Carlson, A.E., Stoner, J.S., Donnelly, J.P., Hillaire-Marcel, C., 2008b. Response of the southern Greenland Ice Sheet during the last two deglaciations. Geology 36, 359-362.

Carlson, A.E., Tarasov, L., Pico, T., 2018. Rapid Laurentide ice-sheet advance towards southern last glacial maximum limit during marine isotope stage 3. Quat. Sci. Rev. 196, 118-123.

Ceperley, E., Marcott, S., Rawling III, J.E., Zoet, L., Zimmerman, S., 2019. The role of permafrost on the morphology of an MIS 3 moraine from the southern Laurentide Ice Sheet. Geology in press.

Church, J.A., Clark, P.U., Cazenave, A., Gregory, J.M., Jevrejeva, S., Levermann, A., Merrifield, M.A., Milne, G.A., Nerem, R.S., Nunn, P.D. Payne, A.J., Pfeffer, W.T., Stammer, D., Unnikrishnan, A.S., 2013. Sea Level Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Clark, P.U., Mix, A.C., 2002. Ice sheets and sea level at the Last Glacial Maximum. Quat. Sci. Rev. 21, 1-7.

Clark, P.U., Tarasov, L., 2014. Closing the sea level budget at the Last Glacial Maximum. Proceed. Nat. Acad. Sci. 111, 15861-15862.

Clark, P.U., Clague, J.J., Curry, B.B., Dreimanis, A., Hicock, S.R., Miller, G.H., Berger, G.W., Eyles, N., Lamothe, M., Miller, B.B., Mott, R.J., Oldale, R.N., Stea, R.R., Szabo, J.P., Thorleifson, L.H., Vincent, J.-S., 1993. Initiation and development of the Laurentide and Cordilleran ice sheets following the last interglaciation. Quat. Sci. Rev. 12, 79-114.

Clark, P.U., Dyke, A.S., Shakun, J.D., Carlson, A.E., Clark, J., Wohlfarth, B., Hostetler, S.W., Mitrovica, J.X., McCabe, A.M., 2009. The Last Glacial Maximum. Science 325, 710-714.

Clark, P.U., Shakun, J.D., Marcott, S.A., Mix, A.C., Eby, M., Kulp, S., Levermann, A., Milne, G.A., Pfister, P.L., Santer, B.D., Schrag, D.P., Solomon, S., Stocker, T.F., Strauss, B.H., Weaver, A.J., Winkelmann, R., Archer, D., Bard, E., Goldner, A., Lambeck, K., Pierrehumbert, R.T., Plattner, G.-K., 2016. Consequences of twenty-first-century policy for multi-millennial climate and sea-level change. Nat. Clim. Change, doi: 10.1038/NCLIMATE2923.

Cuzzone, J.K., Clark, P.U., Carlson, A.E., Ullman, D.J., Rinterknecht, V.R., Milne, G.A., Pekka, J., Wohlfarth, B., Marcott, S.A., Caffee, M., 2016. Final deglaciation of the Scandinavian Ice Sheet and implications for the Holocene global sea-level budget. Earth Planet. Sci. Lett. 448, 34-41.

Dalton, A.S., Finkelstein, S.A., Barnett, P.J., Forman, S.L., 2016. Constraining the late Pleistocene history of the Laurentide ice sheet by dating the Missinaibi formation, Hudson Bay lowlands, Canada. Quat. Sci. Rev. 146, 288-299.

Dalton, A.S., Finkelstein, S.A., Forman, S.L., Barnett, P.J., Pico, T., Mitrovica, J.X., 2019. Was the Laurentide Ice Sheet significantly reduced during Marine Isotope Stage 3? Geology, doi: 10.1130/G45335.1.

Darvill, C.M., Menounos, B., Goehring, B.M., Lian, O.B., Caffee, M.W., 2018. Retreat of the western Cordilleran Ice Sheet margin during the last deglaciation. Geophys. Res. Lett. 45, doi: 10.1029/2018GL079419.

DeConto, R.M., Pollard, D., 2016. Contribution of Antarctica to past and future sea-level rise. Nature 531, 591-597.

Denton, G.H., Hughes, T.J., 1981. The Last Great Ice Sheets, Wiley, New York, 484pp.

Denton, G.H., Anderson, R.F., Toggweiler, J.R., Edwards, R.L., Schaefer, J.M., Putnam. A.E., 2010. The last glacial termination. Science 328, 1652-1656.

Donn, W.L., Farrand, W.R., Ewing, M., 1962. Pleistocene ice volumes and sea-level lowering. J. Geol. 70, 206-214.

Dutton, A., Carlson, A.E., Long, A.J., Milne, G.A., Clark, P.U., DeConto, R., Horton, B., Rahmstorf, S., Raymo, M.E., 2015a. Sea-level rise due to polar ice-sheet mass loss during past warm periods. Science 349, 153.

Dutton, A., Webster, J.M., Zwartz, D., Lambeck, K., Wohlfarth, B., 2015b. Tropical tales of polar ice: evidence of Last Interglacial polar ice sheet retreat recorded by fossil reefs of the granitic Seychelles islands. Quat. Sci. Rev. 107, 182-196.

Edwards, T.L., Brandon, M.A., Durand, G., Edwards, N.R., Golledge, N.R., Holden, P.B., Nias, I.J., Payne, A.J., Ritz, C., Wernecke, A., 2019. Revisiting Antarctic ice loss due to marine ice-cliff instability. Nature 566, 58-64.

Grant, G.R., Sefton, J.P., Patterson, M.W., Naish, T.R., Dunbar, G.B., Hayward, B.W., Morgans, H.E.G., Alloway, B.V., Seward, D., Tapai, C.A., Prebble, J.G., Kamp, P.J.J, McKay, R., Ohneiser, C., Turner, G.M., 2018. Mid- to late Pliocene (3.3-2.6 Ma) global sea-level fluctuations recorded on a continental shelf transect, Whanganui Basin, New Zealand. Quat. Sci. Rev. 201, 241-260.

Hallmann, N., Camoin, G., Eisenhauer, A., Botella, A., Milne, G.A., Vella, C., Samankassou, E., Pothin, V., Dussouillez, P., Fleury, J., Fietzke, J., 2018. Ice volume and climate changes from a 6000 year sea-level record in French Polynesia. Nat. Comm., doi: 10.1038/s41467-017-02695-7.

Jansen, E., Fronval, T., Rack, F., Channell, J.E.T., 2000. Pliocene-Pleistocene ice rafting history and cyclicity in the Nordic Seas during the last 3.5 Myr. Paleoceanography 15, 709-721.

Kingslake, J., Scherer, R.P., Albrecht, T., Coenen, J., Powell, R.D., Reese, R., Stansell, N.D., Tulaczyk, S., Wearing, M.G., Whitehouse, P.L., 2018. Extensive retreat and re-advance of the West Antarctic Ice Sheet during the Holocene. Nature 558, 430-434.

Kopp, R.E., Kemp, A.C., Bittermann, K., Horton, B.P., Donnelly, J.P., Gehrels, W.R., Hay, C.C., Mitrovica, J.X., Morrow, E.D., Rahmstorf, S., 2016. Temperature-driven global sea-level variability in the Common Era. Proceed. Nat. Acad. Sci., doi: 10.1073/pnas.1517056113.

Kopp, R.E., Simons, F.J., Mitrovica, J.X., Maloof, A.C., Oppenheimer, M., 2013. A probabilistic assessment of sea level variations within the last interglacial stage. Geophys. J. Int., doi: 10.1093/gji/ggt029.

Lambeck, K., Rouby, H., Purcell, A., Sun, Y., Sambridge, M., 2014. Sea level and global ice volumes from the last glacial maximum to the Holocene. Proc. Natl. Acad. Sci., doi: 10.1073/pnas.1411762111.

Larsen, N.K., Kjær, K.H., Lecavalier, B., Bjørk, A.A., Colding, S., Huybrechts, P., Jakobsen, K.E., Kjeldsen, K.K., Knudsen, K.-L., Odgaard, B.V., Olsen, J., 2015. The response of the southern Greenland ice sheet to the Holocene thermal maximum. Geology, doi: 10.1130/G36476.1.

Larsen, N.K., Levy, L.B., Carlson, A.E., Buizert, C., Olsen, J., Strunk, A., Bjørk, A.A., Skov, D.S., 2018. Instability of the Northeast Greenland Ice Stream over the last 45,000 years. Nat. Commun., doi: 10.1038/s41467-018-04312-7.

Laskar, J., Robutel, P., Joutel, F., Gastineau, M., Correia, A.C.M., Levrard, B., 2004. A long-term numerical solution for the insolation quantities of the Earth. Astronomy & Astrophysics 428, 261-285.

Lesnek, A.J., Briner, J.P., Lindqvist, C., Baichtal, J.F., Heaton, T.H., 2018. Deglaciation of the Pacific coastal corridor directly preceded the human colonization of the Americas. Sci. Adv. 4, eaar5040.

Lisiecki, L.E., Raymo, M.E., 2005. A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}O$ records. Paleoceanography 20, doi: 10.1029/2004PA001071.

Martínez-Botí, M.A., Foster, G.L., Chalk, T.B., Rohling, E.J., Sexton, P.F., Lunt, D.J., Pancost, R.D., Badger, M.P.S., Schmidt, D.N., 2015. Plio-Pleistocene climate sensitivity evaluated using high-resolution CO_2 records. Nature 518, 49-54.

Meyers, S.R., Hinnov, L.A., 2010. Northern Hemisphere glaciation and the evolution of Plio-Pleistocene climate noise. Paleoceanography 25, doi: 10.1029/2009PA001834.

Mix, A.C., Pisias, N.G., Rugh, W., Wilson, J., Morey, A., Hagelberg, T.K., 1995. Benthic foraminifer stable isotope record from Site 849 (0–5 Ma): local and global climate changes. Proc. ODP, Sci. Results 138, 371–412.

Patterson, M.O., McKay, R., Naish, T., Escutia, C., Jimenez-Epejo, F.J., Raymo, M.E., Meyers, S.R., Tauxe, L., Brinkhuis, H., IODP Expedition 318 Scientists, 2014. Orbital forcing of the East Antarctic ice sheet during the Pliocene and early Pleistocene. Nat. Geosci., doi: 10.1038/NGEO2273.

Pearson, P.N., Palmer, M.R., 2000. Atmospheric carbon dioxide concentrations over the past 60 million years. Nature 406, 695-699.

Peltier, W.R., Fairbanks, R.G., 2006. Global glacial ice volume and Last Glacial Maximum duration from an extended Barbados sea level record. Quat. Sci. Rev. 25, 3322-3337.

Pico, T., Birch, L., Weisenberg, J., Mitrovica, J.X., 2018. Refining the Laurentide Ice Sheet at Marine Isotope Stage 3: A data-based approach combining glacial isostatic simulations with a dynamic ice model. Quat. Sci. Rev. 195, 171-179.

Pico, T., Creveling, J.R., Mitrovica, J.X., 2017. Sea-level records from the U.S. Mid-Atlantic constrain Laurentide ice sheet extent during marine isotope stage 3. Nat. Commun., doi: 10.1038/ncomms15612.

Polyak, V.J., Onac, B.P/., Fornós, J.J., Hay, C., Asmerom, Y., Dorale, J.A., Ginés, J., Tuccimei, P., Ginés, A., 2018. A highly resolved record of relative sea level in the western Mediterranean Sea during the last interglacial period. Nat. Geosci., doi: 10.1038/s41561-018-0222-5.

Raymo, M.E., Lisiecki, L.E., Nisancioglu, K.H., 2006. Plio-Pleistocene ice volume, Antarctic climate, and the global $\delta^{18}O$ record. Science 313, 492-495.

Romundset, A., Lakeman, T.R., Høgaas, F., 2018. Quantifying variable rates of postglacial relative sea level fall from a cluster of 24 isolation basins in southern Norway. Quat. Sci. Rev. 197, 175-192.

Simms, A.R., Lisiecki, L., Gebbie, G., Whitehouse, P.L., Clark, J.F., 2019. Balancing the last glacial maximum (LGM) sea-level budget. Quat. Sci. Rev. 205, 143-153.

Simms, A.R., Whitehouse, P.L., Simkins, L.M., Nield, G., DeWitt, R., Bentely, M.J., 2018. Late Holocene relative sea levels near Palmer Station, northern Antarctic Peninsula, strongly controlled by late Holocene ice-mass changes. Quat. Sci. Rev. 199, 49-59.

Skrivanek, A., Li, J., Dutton, A.E., 2018. Relative sea-level change during the Last Interglacial as recorded in Bahamian fossil reefs. Quat. Sci. Rev. 200, 160-177.

Solomina, O.N., Bradley, R.S., Hodgson, D.A., Ivy-Ochs, S., Jomelli, V., Mackintosh, A.N., Nesje, A., Owen, L.A., Wanner, H., Wiles, G.C., Young, N.E., 2015. Holocene glacier fluctuations. Quat. Sci. Rev. 111, 9-34.

Thompson, W.G., Curran, H.A., Wilson, M.A., White, B., 2011. Sea-level oscillations during the last interglacial highstand recorded by Bahamas corals. Nat. Geosci., doi: 10.1038/NGEO1253.

Ullman, D.J., Carlson, A.E., Hostetler, S.W., Clark, P.U., Cuzzone, J.K., Milne, G.A., Winsor, K., Caffee, M., 2016. Final deglaciation of the Laurentide ice sheet in the early to middle Holocene. Quat. Sci. Rev. 152, 49-59.

Wood, J.R., Forman, S.L., Everton, D., Pierson, J., Gomez, J., 2010. Lacustrine sediments in Porter Cave, Central Indiana, USA and possible relation to Laurentide ice sheet marginal positions in the middle and late Wisconsinan. Palaeogeog., Palaeoclim., Palaeoecol. 298, 421-431.

Xiong, H., Zong, Y., Qjan, P., Huang, G., Fu., S., 2018. Holocene sea-level history of the northern coast of South China Sea. Quat. Sci. Rev. 194, 12-26.

Yokoyama, Y., Hirabayashi, S., Goto, K., Okuno, J., Sproson, A.D., Haraguchi, T., Ratnayake, N., Miyairi, Y., 2019. Holocene Indian Ocean sea level, Antarctic melting history and past Tsunami deposits inferred using sea level reconstructions from the Sri Lankan, Southeastern Indian and Maldivian coasts. Quat. Sci. Rev. 206, 150-161.

Yousefi, M., Milne, G.A., Love, R., Tarasov, L., 2018. Glacial isostatic adjustment along the Pacific coast of central North America. Quat. Sci. Rev. 193, 288-311.

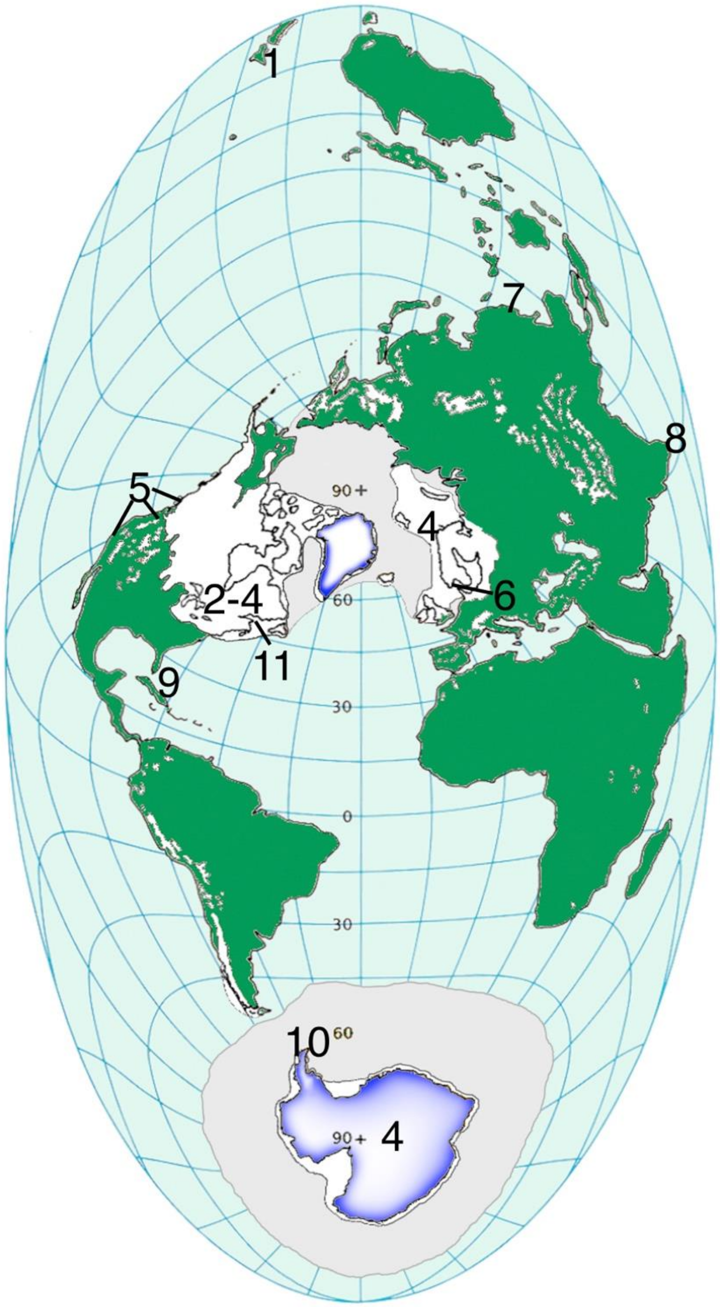

Fig. 1. Map of ice-sheet extent at the last glacial maximum (Denton et al., 2010). Numbers indicate the location of studies in this special issue: 1 – Grant et al. (2018); 2 – Carlson et al. (2018); 3 – Pico et al. (2018); 4 – Simms et al. (2019a); 5 – Yousefi et al. (2018); 6 – Romundset et al. (2018); 7 – Xiong et al. (2018); 8 – Yokoyama et al. (2019); 9 – Skrivanek et al. (2018); 10 – Simms et al. (2018b); 11 – Barnett et al. (2019).

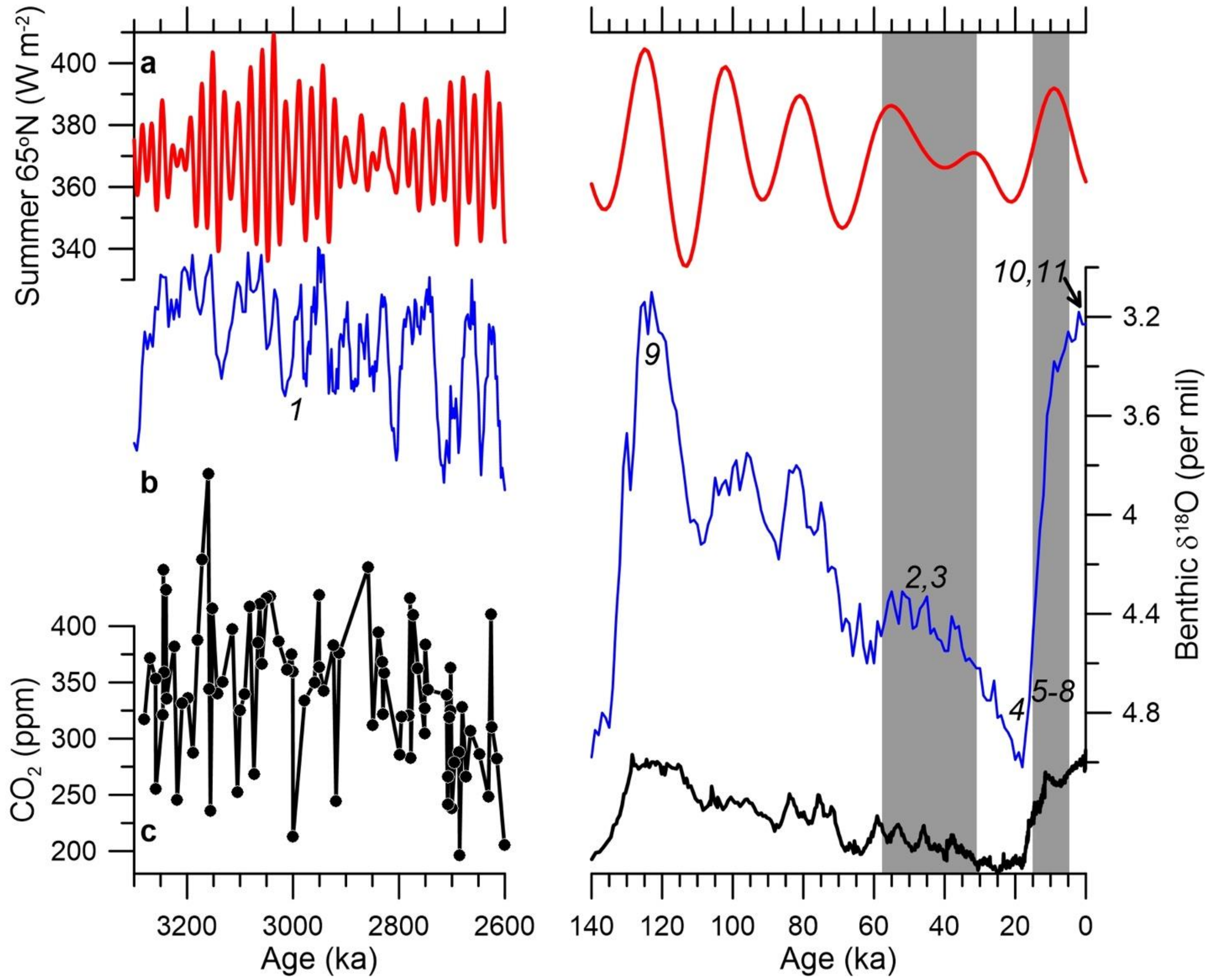

Fig. 2. Time series for the late Pliocene (left) and the last glacial cycle (right). (**a**) Summer (average of summer solstice to fall equinox) insolation at 65°N (Laskar et al., 2004). (**b**) benthic $\delta^{18}O$ (Lisiecki & Raymo, 2005). Italics numbers (see Fig. 1) indicate the time periods covered by individual studies in this special issue, with gray bars denoting the range of study during marine isotope stage 3 and the early to middle Holocene. (c) Atmospheric CO_2 concentration from planktic foraminfer $\delta^{11}B$ (left with symbols; Pearson & Palmer, 2000; Bartoli et al., 2011; Martínez-Botí et al., 2015) and ice-core measurements (right with thick line; Bereiter et al., 2015).